

ILWS2016 School on Space Weather

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## Near-Earth particle environment relevant to space weather

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Thanks to organizers

The particles:

*Ring Current, Radiation Belts, Plasmasphere*

Space weather phenomenon connecting them:

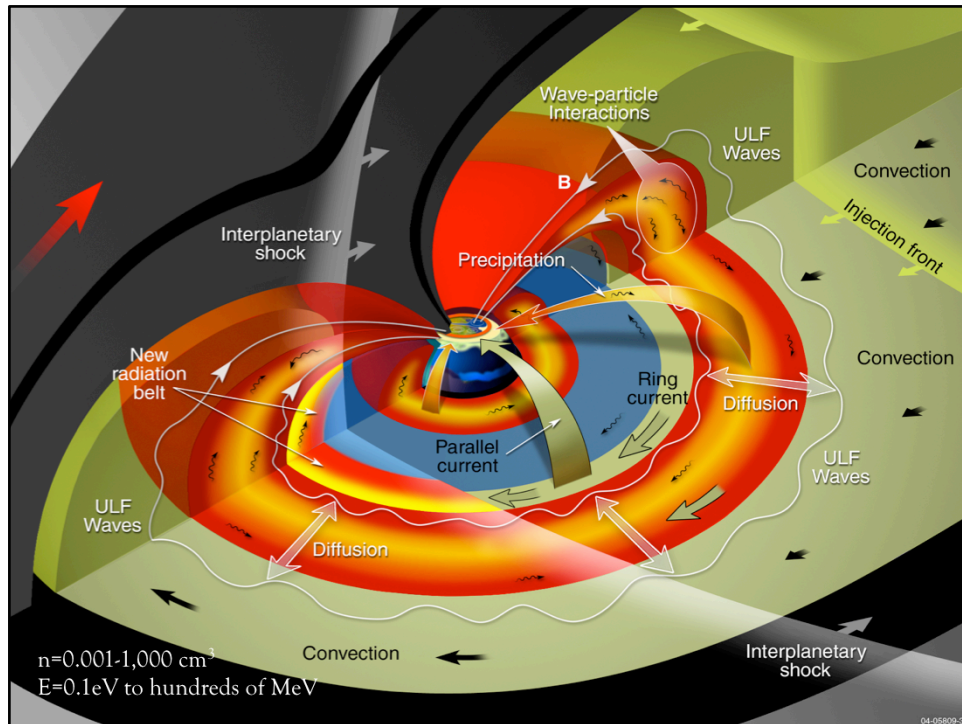
*Space storm (aka geospace magnetic storm)*



Aka geomagnetic storm, space storm, magnetic storm.

Space Storms include the occurrence of impulsive DC electric fields and of low-frequency electromagnetic waves





**Huge span of 9 orders of magnitude in energy and 6 orders of magnitude in density.**

Air molecules in the atmosphere only have about 0.03 eV, Protons in the inner belt: a couple of hundreds of million eV

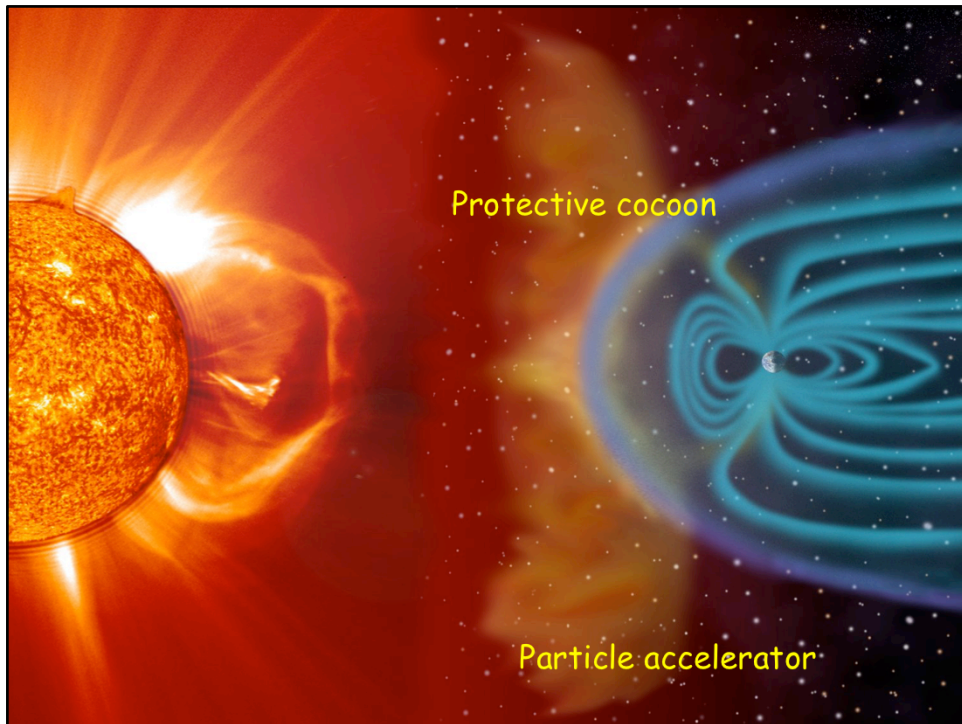
This raises the most fundamental question in space research - **how come a few particles get so much?**

Mass:  $\sim 10^5$  kg (100 tons) PEANUTS ... 100 cars ... The thin **Atmosphere:  $\sim 10^{18}$ , i.e. one million millions the mass of msph**

Half an eV equals to the energy of a particle on Sun's surface ( $T=5,800$  K,  $1 \text{ eV} = 11,600$  K).

0.67 eV: The energy needed by a proton or neutron to escape the Earth's gravity.

40,000 eV: Energy required by an electron to penetrate a thin-wall Geiger counter like that of Explorer 1.



Magnetosphere: a protective cocoon for the Earth. Let me emphasize that however intense a solar flare may be, there is pretty much no effect in Geospace if the magnetospheric magnetic field is not influenced by a particular topology of the IMF. There is much too often a misconception about the way the Sun influences dynamic processes in Geospace.

**The release of energy from the sun is an absolutely necessary condition, but it is not enough.** The magic word is magnetic connectivity

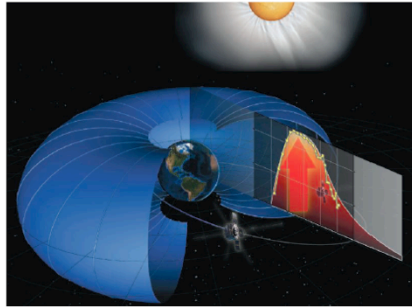
Now the fun and interesting fact is that Geospace is also a rather efficient cosmic accelerator. And because of this, it is the **cradle of disaster.**

SPACE PHYSICS

## The Savage Radiation of the Van Allen Belts Is Homegrown

Back in 1958, Explorer 1, the first U.S. satellite, sent back unsettling news: Nearby space was pervaded by radiation intense enough to blind their instruments. The Van Allen radiation belts, extending from about 1000 kilometers to 60,000 kilometers from Earth, have been zapping unlucky satellites—and puzzling space physicists—ever since. Now, at last, researchers have figured out where the electrons that fill the Van Allen belts get their killer energy. A pair of probes launched last year has traced how energy streaming from the sun can boost electrons in the heart of the belts to speeds greater than 99% of the speed of light.

Researchers “have found the key signature” of electrons being accelerated



**Inner turmoil.** Electron energies (yellow curve) detected by two new spacecraft peak inside the radiation belts (including the magnetically defined blue torus) as expected for in situ acceleration (gray curve).

the outer belt, as some theories predicted, the data showed that energy surged among low-energy electrons already in the belts, Reeves says. Powerful electromagnetic waves in the solar wind were almost certainly transferring their energy to the resident electrons, boosting them to speeds at which they can fry a satellite's electronics.

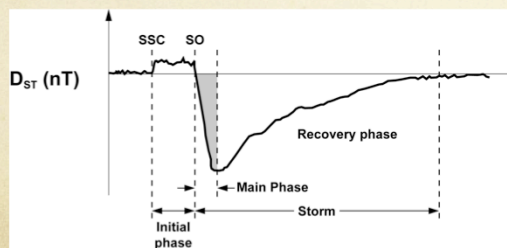
It's still unclear which of a half dozen kinds of waves is the primary driver. But the most likely energy source, Reeves says, is so-called chorus waves, so named because, when converted to sound, their natural frequencies resemble a dawn chorus of birds. Chorus waves that are in sync with electrons spiraling about magnetic field lines would

Science, 2013

This is a characteristic article title -

## Space Storms

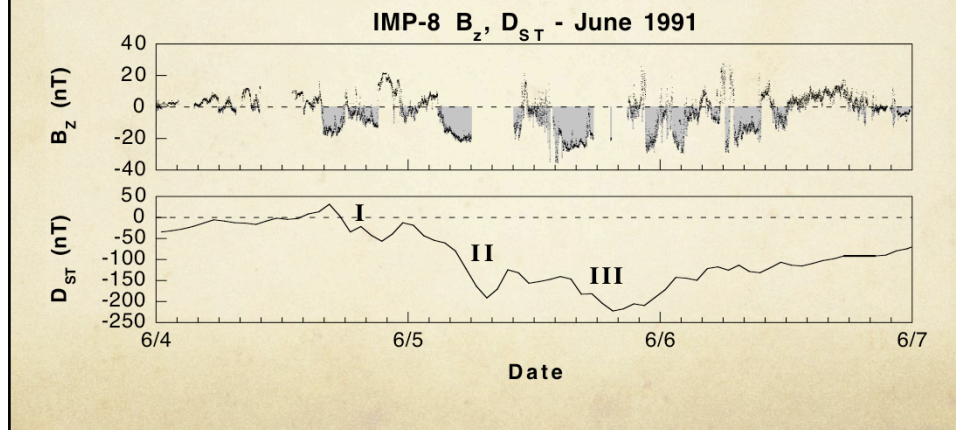
- Historically defined (and identified) as prolonged world-wide depression of H-component of geomagnetic field
- Associated with aurora and solar eruptions
- Now recognized as the most complex, multi-faceted dynamic phenomenon in geospace



Global Geomagnetic Field Depression which can be explained through the diamagnetic effect of a giant (ring) current flowing around the Earth.

## Space Storms

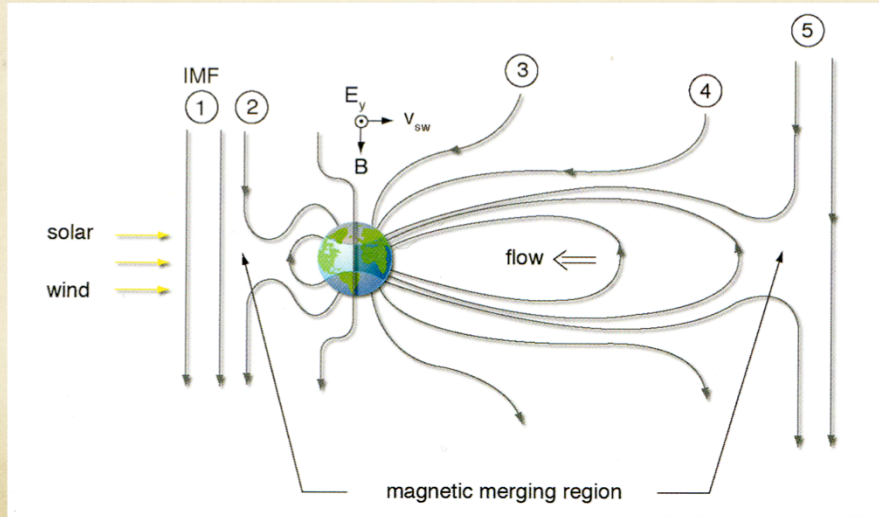
Require prolonged SW-magnetosphere coupling  
(many hours of southward IMF)



Energy requirement: many hours of southward IMF, leading to extensive magnetic reconnection and increase of magnetic flux in the terrestrial magnetosphere. Usually associated with CMEs.



## Magnetic reconnection: Transforming magnetic to kinetic energy



**The fundamental process: Magnetic Reconnection on the Sun and in Geospace.**

## Space Storms

Not to be confused with Solar Storms,  
(aka Solar Radiation Storms)  
which are episodes of intense acceleration  
of solar particles to very high energies  
(**S**olar **E**nergetic **P**articles – SEPs)  
by solar flares and/or CMEs.

**particles from the solar corona**

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Solar Storms and Space Storms **are not identical!**

## Space Storms

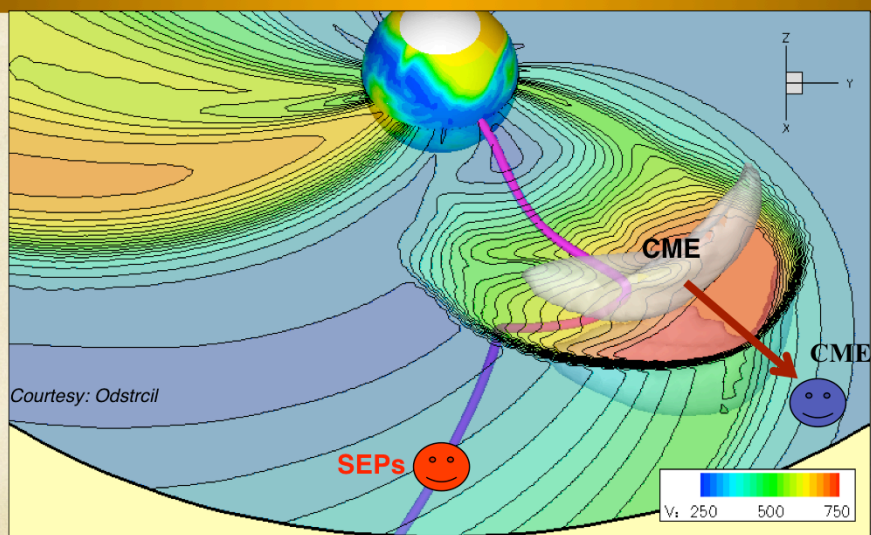
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Solar Storms and Space Storms **are not identical!**

Solar Storms **do not cause** Space Storms!

(frequent mistake of public outreach articles)

## CME and SEP paths are different

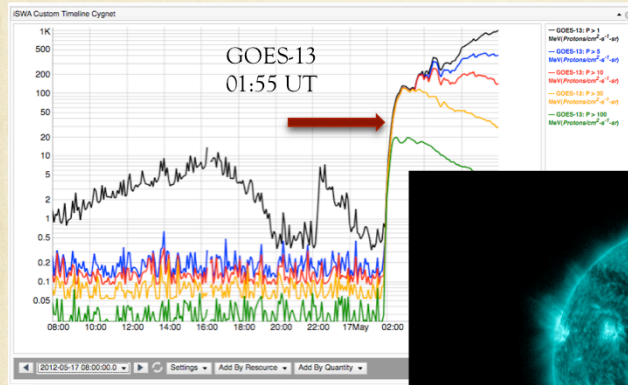


CME: could get deflected, bended, but more or less in the radial direction

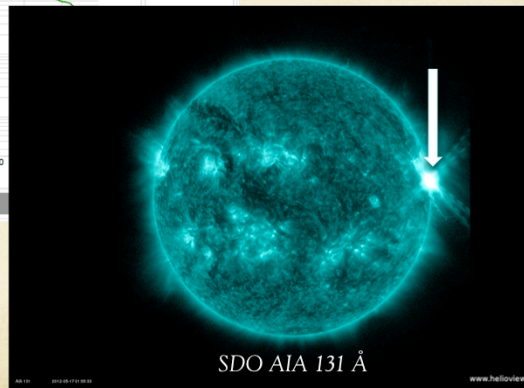
**Magnetic connectivity!**



For Earth – “Best” Connection is 45-60 degrees west



*Energetic proton fluxes  
elevated for >12 hours*



NOAA categorizes Solar Radiation Storms using the NOAA Space Weather Scale on a scale from S1 - S5. The scale is based on measurements of energetic protons taken by the GOES satellite in geosynchronous orbit. The start of a Solar Radiation Storm is defined as the time when the flux of protons at energies  $\geq 10$  MeV equals or exceeds 10 proton flux units (1 pfu = 1 particle\*cm<sup>-2</sup>\*s<sup>-1</sup>\*ster<sup>-1</sup>). The end of a Solar Radiation Storm is defined as the last time when the flux of  $\geq 10$  MeV protons is measured at or above 10 pfu. This definition allows multiple injections from flares and interplanetary shocks to be encompassed by a single Solar Radiation Storm. A Solar Radiation Storm can persist for time periods ranging from hours to days.

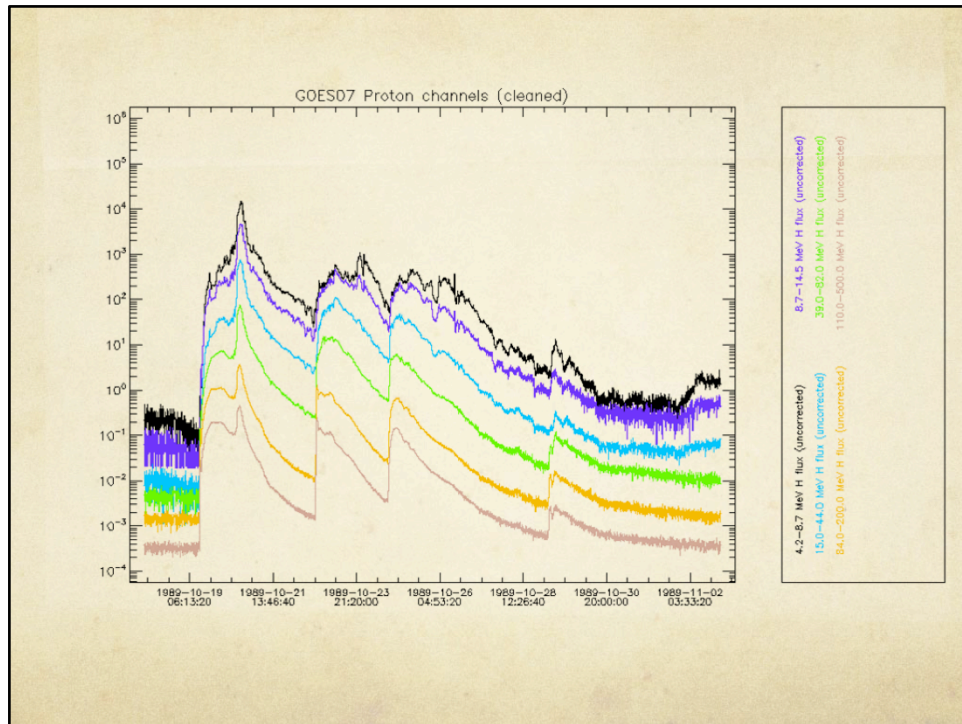
## Solar radiation storms

Solar Energetic Particles (SEPs)

Flux of energetic ions  $>10$  MeV

|       |   |          |   |         |   |        |   |            |
|-------|---|----------|---|---------|---|--------|---|------------|
| 10    | – | $10^2$   | – | $10^3$  | – | $10^4$ | – | $10^5$     |
| Minor | – | Moderate | – | Strong  | – | Severe | – | Extreme    |
|       |   |          |   | 10/s.c. |   | 3/s.c. |   | $<1$ /s.c. |

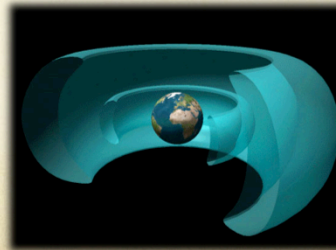
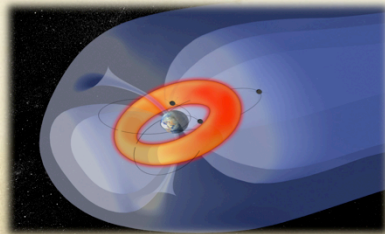
The crucial importance of Magnetic connectivity is probably the reason why extreme solar storms, with very high fluxes of SEPs, are so rare at Earth's orbit.  
Compare to 175 X1 flares / s.c.



An example of a **STRONG** solar storm

## Ring Current (RC) and Van Allen Belts (RBs)

- RC: Carried mainly by ions ( $\text{H}^+$ ,  $\text{O}^+$ ,  $\text{He}^{++}$ ,  $\text{He}^+$ ) in the energy range  $\sim 10$  keV to a few 100s keV.  $\sim \text{MA}$   
Region:  $3-5 R_E$
- RBs: protons (inner belt) and electrons (outer belt) in the energy range 100 keV to 20+/400+ MeV.  
Regions:  $1.5-2 R_E$  (inner),  $2-2.5 R_E$  (slot),  $4-5 R_E$  (outer)

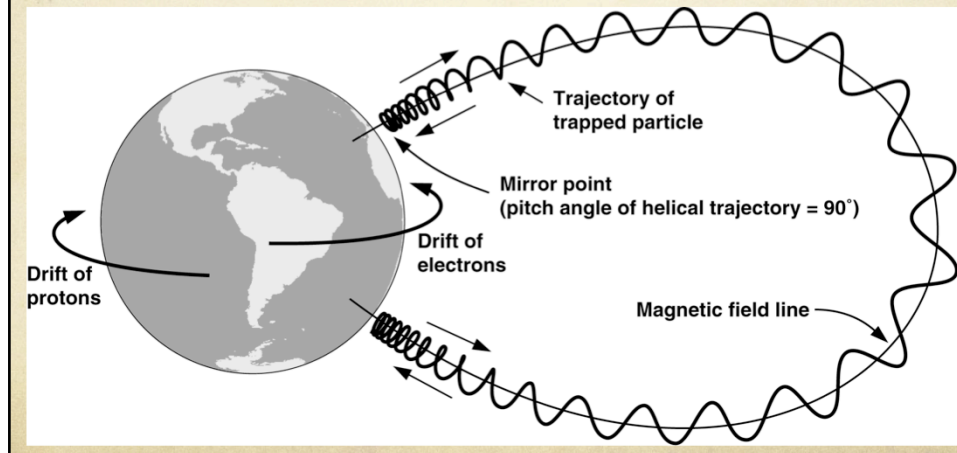


RC: of both solar and terrestrial origin. **Total intensity of several Mega Amperes.**  
Bulk of energy within 50-100 keV. Maximum intensity at  $3-5 R_E$  (geocentric)



## Ring Current (RC) and Van Allen Belts (RBs)

Same principle:  
combination of 3 periodic motions (gyro, bounce and drift)  
corresponding to three adiabatic invariants



and leading to a toroidal topology

## Periodic motions and adiabatic invariants

### □ 1<sup>st</sup> adiabatic invariant

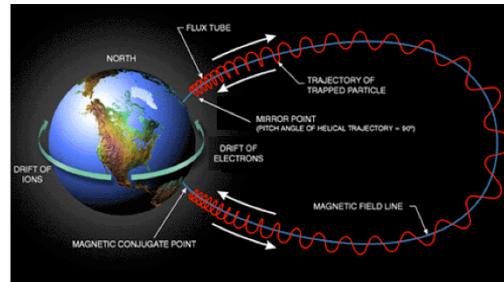
$$\mu = \frac{p_{\perp}^2}{2mB} \Rightarrow \mu = \frac{p^2 \sin^2 \alpha}{2mB}$$

### □ 2<sup>nd</sup> adiabatic invariant

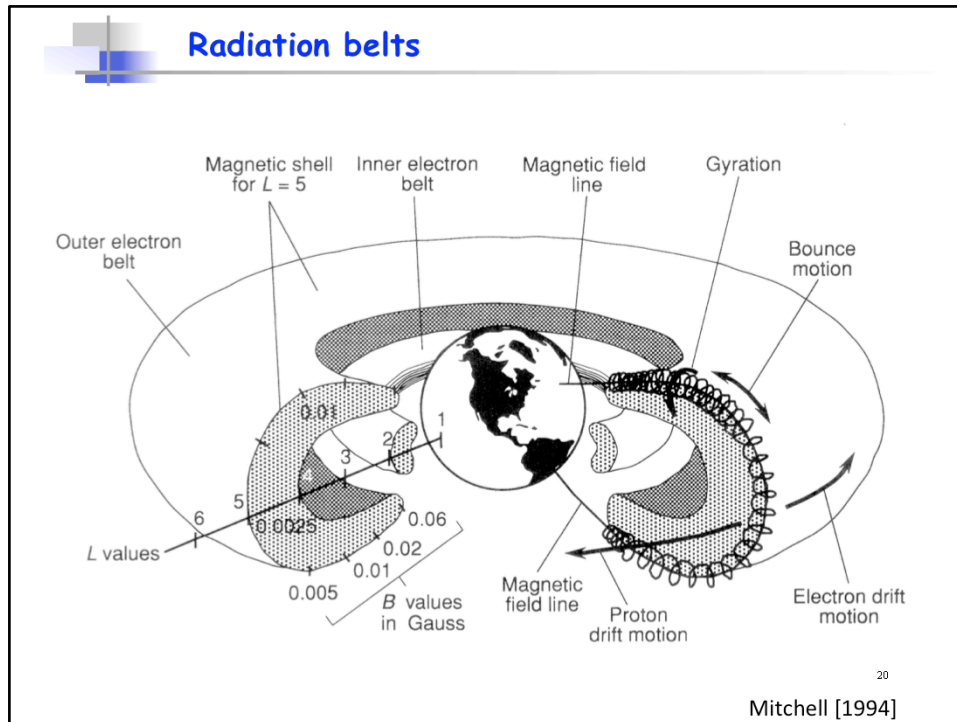
$$J = (8m_0\mu)^{1/2} \int_{a_m}^{b_m} B_m - B(s) ds$$

### □ 3<sup>rd</sup> adiabatic invariant

$$\Phi = \oint u_{drift} r d\varphi$$



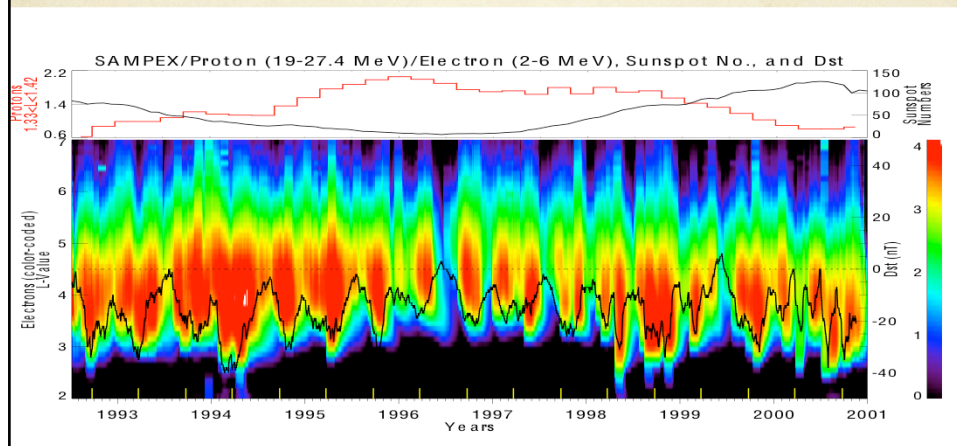
Electrons in the plasma sheet represent a source of high phase space density (PSD), and when the third adiabatic invariant is broken these particles can diffuse inwards in radial distance, gaining energy in the process.



For quite some time the RBs were considered to be a pretty stable structure. There were no dedicated RadBelt missions for more than 3 decades. Even the nowadays considered as RB missions, CRRES and SAMPEX missions, had different main objectives. CRRES intended to study the Radiation Effects on new generation electronics – not the radiation itself! – while SAMPEX’s main objectives were the galactic cosmic rays (from supernova explosions in our Galaxy); anomalous cosmic rays (from the interstellar gas surrounding our solar system); and solar energetic particles.

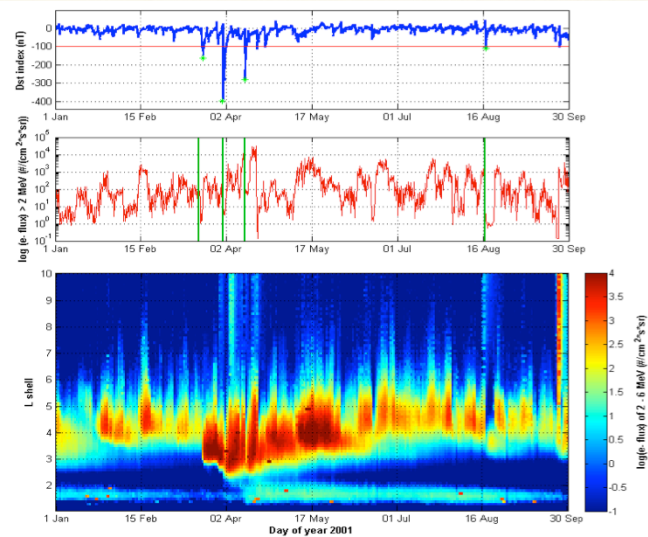
## Storms and RBs

Successive paradigm shifts:  
From quasi-linear diffusion theory  
to dramatic variability on short time scales



**SAMPEX observations 1991-2001.** Fluxes vary by 4 to 5 orders of magnitude (Xinlin Li et al. 2001) on time scales down to minutes

## Storms and RBs



Fluxes increase by  $> 5$  orders of magnitude,  
and penetration to very low L-shells

However, there ARE storms, during which the flux increase of relativistic electrons and the earthward penetration is very impressive.  
March – April 2001 storm



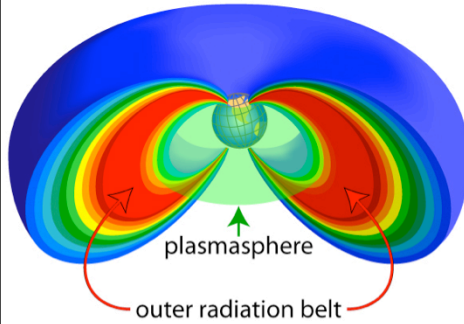
## Storms and RBs

Net Loss or Net Gain:  
the synergistic result  
of a mixture of collaborating or competing  
acceleration, transport and loss processes  
involving waves and plasmas

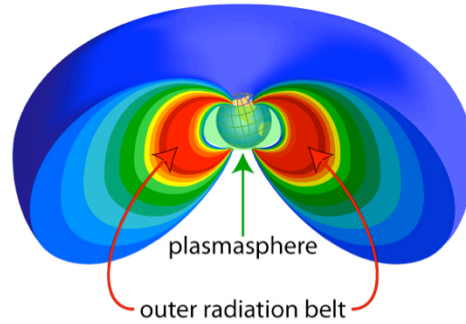
involving waves and plasmas **and their interactions**

## Van Allen Belt Dynamics

a. Normal plasmasphere/radiation belt location under typical conditions

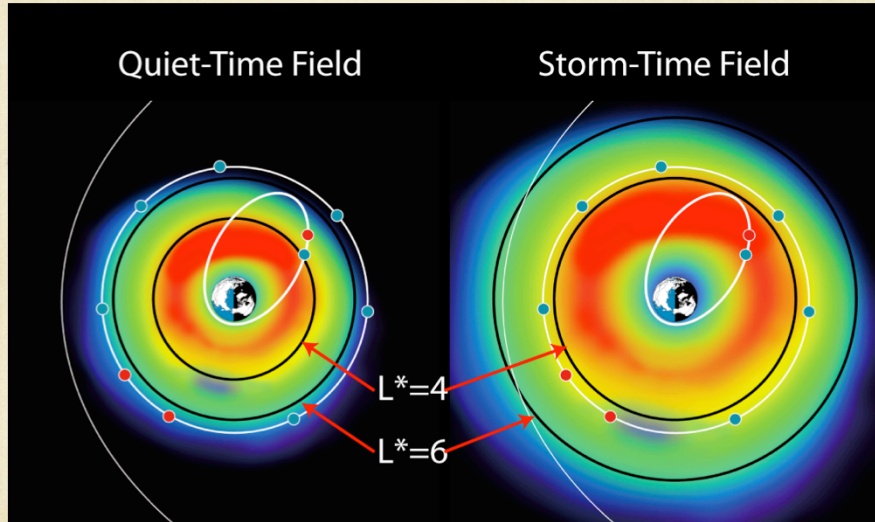


b. Distorted plasmasphere/radiation belt during October/November 2003 storm



We further have realized that the coldest plasmas control the hottest particles – because the cold plasmaspheric plasma influences the propagation of electromagnetic waves, which can accelerate electrons to relativistic energies.

## Storms and RB losses



"Dst effect": adiabatic (reversible) losses due to B-reconfigurations

**The Dst effect:** adiabatic effect due to the temporary reconfiguration of the near-Earth B-field

## Storms and RB losses

Non-adiabatic (irreversible) losses due to

1. pitch-angle scattering into the  
**atmospheric loss cone**

EMIC or chorus waves, plasmaspheric hiss

2. **magnetopause** shadowing

via outward radial diffusion & magnetopause compression  
PC5 waves

### **Hiss Generation mechanisms under debate**

Both the PC5 waves that cause radial diffusion, and the SW high pressure are usually associated with magnetic storms

**Chorus waves are associated with substorms, which are more numerous and stronger during storms.**

## Storms and RB acceleration

**This combination yields strong increases of relativistic  $e^-$**

**(i) inward radial diffusion** fueled by enhanced storm-time convection and substorm injections, provides a seed population of 10s-100s keV  $e^-$  to outer belt. Seed  $e^-$  are further accelerated to relativistic energies through

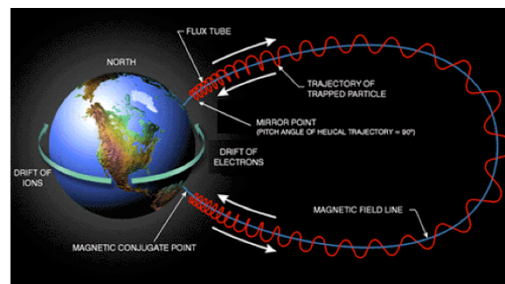
**(ii) local acceleration via wave-particle interactions** by lower band chorus waves

**Inward radial diffusion**, supported by storm-time enhanced convection and substorm injections provides a seed population of 10s to 100s keV  $e^-$ , which are accelerated to relativistic energies by lower band chorus waves (ii)



## Radial diffusion

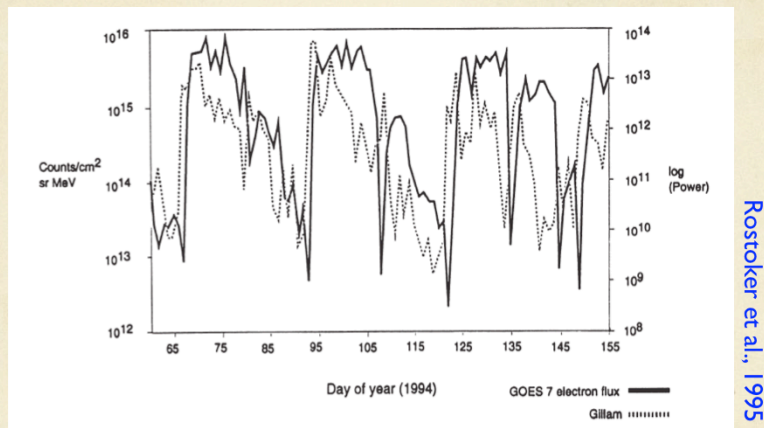
Pc5 waves with period matching the particle drift motion period can break the drift invariant. Earthward radial diffusion results in increased flux levels as particles are transported to regions of stronger magnetic fields.



Inward radial diffusion is driven by Pc5 waves, which have periods matching the particle drift motion period, and therefore break the drift invariant, **while maintaining the gyro and bounce invariants, can break the drift invariant**



## Pc5 waves – RB connection

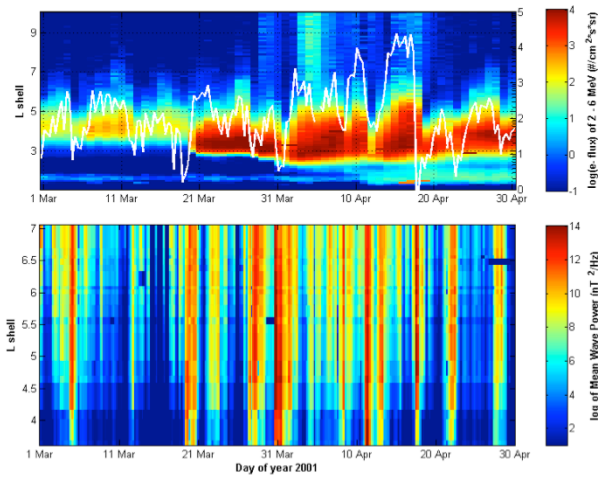


Increases in the Pc5 wave power  
observed by ground magnetometers match  
increases of the relativistic electron flux observed by GOES-7

**Pc5 waves have been closely tied to dynamical variations in the radiation belts.**

This observation forged / supported the paradigm of diffusion-controlled RB variability.

## Pc5 waves – RB connection



Latitudinal distribution of electron fluxes  $> 2$  MeV and Pc5 wave activity during the period from 1 March to 30 April 2001 [Georgiou et al., 2015]

**Discrete enhancement and penetration of relativ. el., concurrently with Pc5 enhancement and penetration**

## RC – RB connection

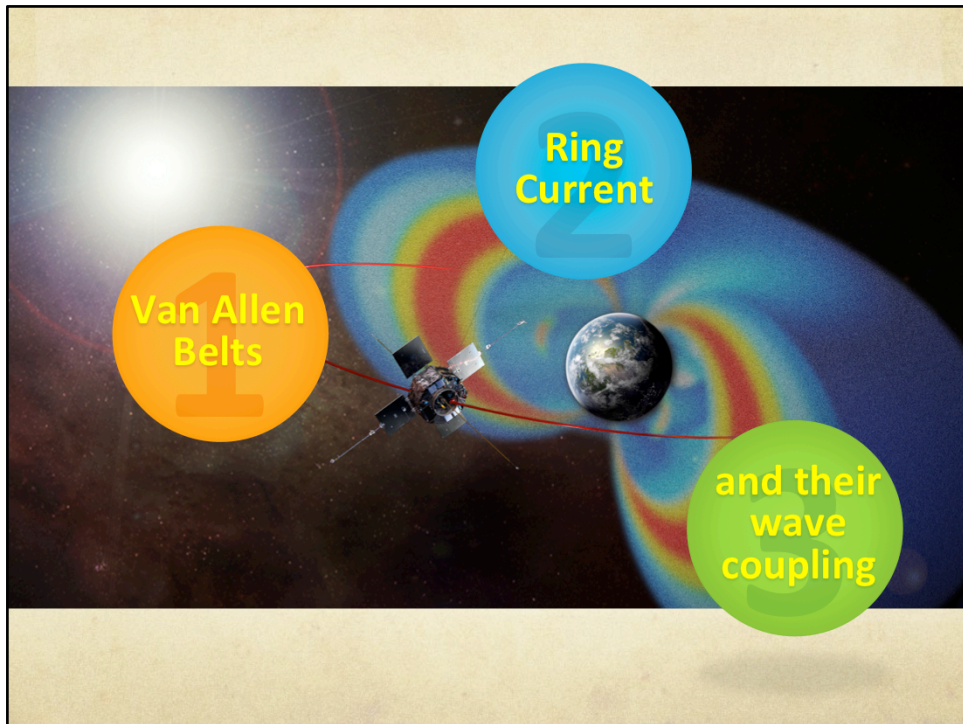
RC  $O^+$  ions have an unstable distribution function in the energy range of 10s of keV and can therefore provide a **source of free energy to drive Pc5 waves**.

Considering that  $O^+$  are the dominant ions during intense storms, it is conceivable that internal magnetospheric driving of Pc5 waves is particularly effective during intense storms.

**There are a couple of ways the RC can influence RB dynamics through its effects on wave growth.**

Low-frequency mirror and drift Instabilities and anisotropies of ring current ions significantly contribute to the growth of Pc5 waves.

$O^+$  in particular ...



## RC – RB connection

The activity level of chorus waves depends on substorm injections.

Substorm injections tend to penetrate increasingly deeper into the inner magnetosphere with increasing  $O^+$  density.

This may contribute to the expansion of chorus wave activity and, consequently, to a spatially more extended electron acceleration.

The activity level of chorus waves, which accelerate  $e^-$  to relativistic energies, depends on substorm injections – i.e. on the same mechanism that contributes to the enhancement of the storm-time ring current.



## RC - Waves – RB connection

Ring current contributing to wave growth

and leading to synergy between

**Pc5** waves

diffusing electrons earthwards

and **chorus** waves

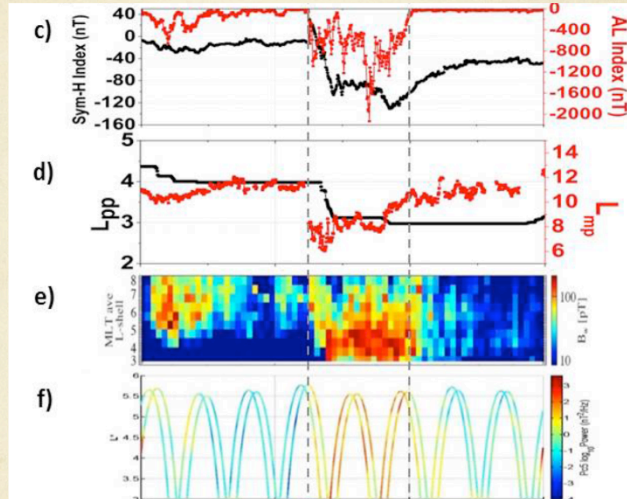
further accelerating them locally

to **relativistic energies**

The RC has the potential of contributing to wave growth and thus to favor the synergy between Pc5 and chorus waves



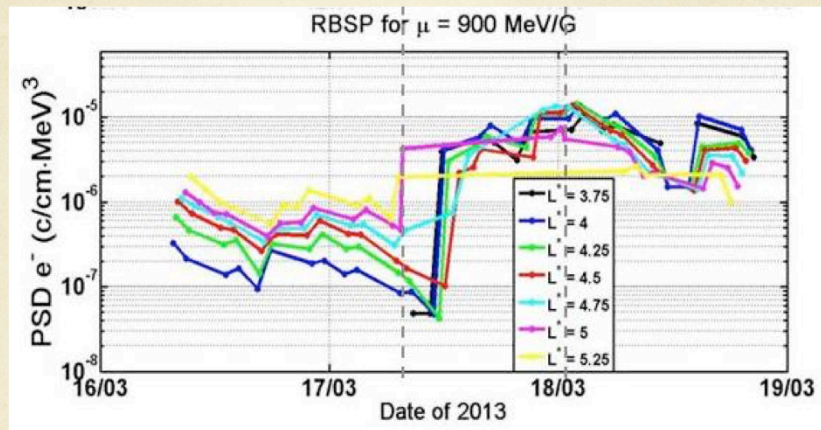
## Storms and RB acceleration



RBSP, 17 March 2013 Storm, Pc5 and Chorus synergy  
[Katsavrias et al., 2015]

A nice example of wave synergy during the intense magnetic storm of March 17, 2013, observed by Van Allen Probes. Data from MAGEIS.  
Chorus wave amplitudes from the ratio of precipitating and trapped electron fluxes over the energy of 30–100 keV (measured by POES satellites)  
Pc5 from the fluxgate magnetometers of RBSP.

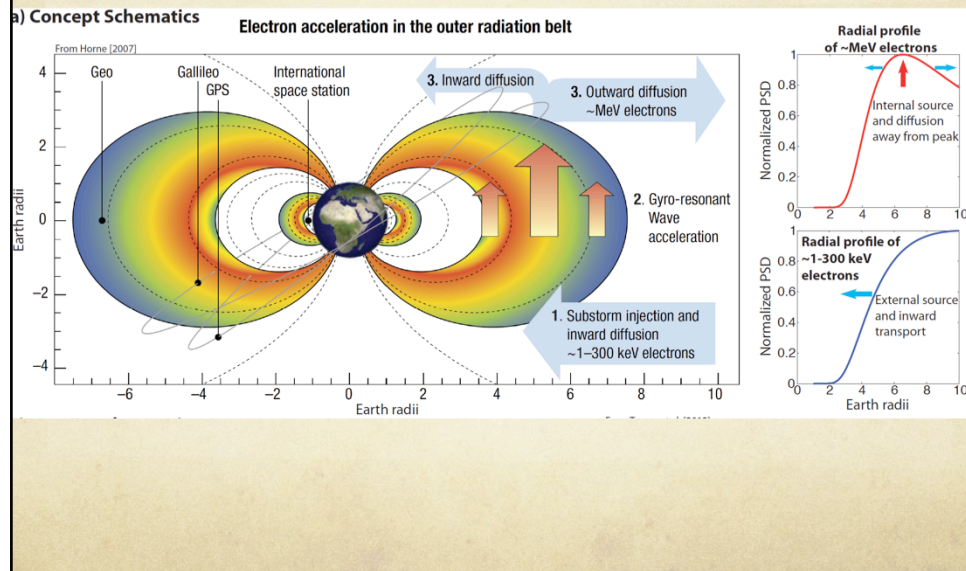
## Storms and RB acceleration



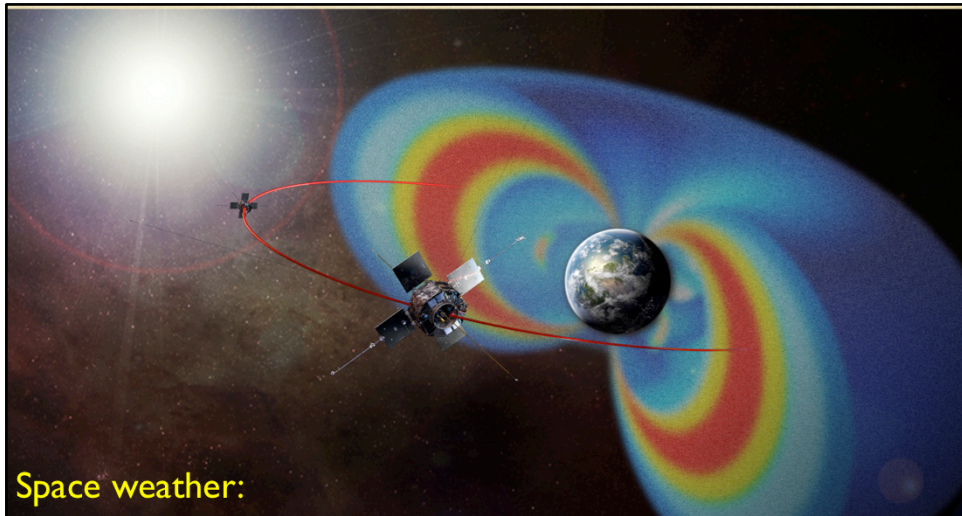
Pc5 and Chorus synergy  
resulting in net enhancement of relativistic electrons

1 MeV electrons

# Storms and RB acceleration




electrons interact with chorus waves via Doppler-shifted cyclotron resonance, resulting in energy diffusion. Provided many such interactions take place as electrons drift around the Earth, individual electrons could be stochastically accelerated up to relativistic energies



### Space weather:

The conditions and phenomena in space, and specifically in the near-Earth environment, that may affect space assets or space operations. Space weather may impact spacecraft and ground-based systems.

|  Space Environment Effects |   |   |
|---|---|---|
| Mechanism   | Effect  | Source  |
| Surface Charging  | <ul style="list-style-type: none"> <li>Biasing of instrument readings</li> <li>Power drains</li> <li>Physical damage</li> </ul>                           | <ul style="list-style-type: none"> <li>Dense, cold plasma</li> <li>Hot plasma</li> </ul>  |
| Deep Dielectric Charging  | <ul style="list-style-type: none"> <li>Biasing of instrument readings</li> <li>Electrical discharges causing physical damage</li> </ul>                   | <ul style="list-style-type: none"> <li>High-energy electrons</li> </ul>   |
| Structure Impacts   | <ul style="list-style-type: none"> <li>Structural damage</li> <li>Decompression</li> </ul>  | <ul style="list-style-type: none"> <li>Micrometeoroids</li> <li>Orbital debris</li> </ul>   |
| Drag  | <ul style="list-style-type: none"> <li>Torques</li> <li>Orbital decay</li> </ul>  | <ul style="list-style-type: none"> <li>Neutral thermosphere</li> </ul>  |
| Total Ionizing Dose (TID)   | <ul style="list-style-type: none"> <li>Degradation of microelectronics</li> </ul>   | <ul style="list-style-type: none"> <li>Trapped protons</li> <li>Trapped electrons</li> <li>Solar protons</li> </ul>                                     |
| Displacement Damage Dose (DDD)  | <ul style="list-style-type: none"> <li>Degradation of optical components and some electronics</li> <li>Degradation of solar cells</li> </ul>              | <ul style="list-style-type: none"> <li>Trapped protons &amp; electrons</li> <li>Solar protons</li> <li>Neutrons</li> </ul>                              |
| Single-Event Effects (SEE)  | <ul style="list-style-type: none"> <li>Data corruption</li> <li>Noise on images</li> <li>System shutdowns</li> <li>Electronic component damage</li> </ul> | <ul style="list-style-type: none"> <li>GCR heavy ions</li> <li>Solar protons and heavy ions</li> <li>Trapped protons</li> <li>Neutrons</li> </ul>       |
| Surface Erosion   | <ul style="list-style-type: none"> <li>Degradation of thermal, electrical, optical properties</li> <li>Degradation of structural integrity</li> </ul>     | <ul style="list-style-type: none"> <li>Particle radiation</li> <li>Ultraviolet</li> <li>Atomic oxygen</li> <li>Micrometeoroids Contamination</li> </ul> |

NASA CCMC 39

From Minow presentation



## Locations of Operational Space Environment Hazards

### Single Event Effects (SEEs)

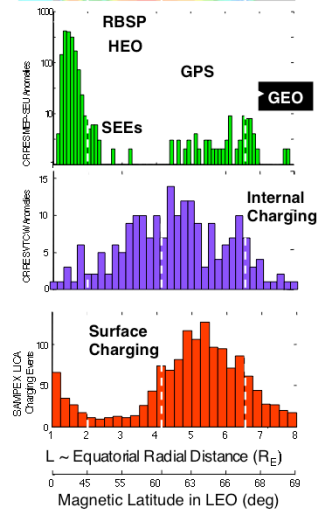
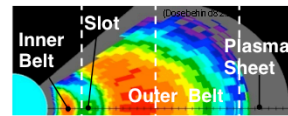
- inner (proton) belt and higher L shells with solar particle event
- quiet-times from galactic cosmic rays

### Internal charging and resulting electrostatic discharges (ESD)

- broad range of L values
- corresponding to the outer belt
- where penetrating electron fluxes are high

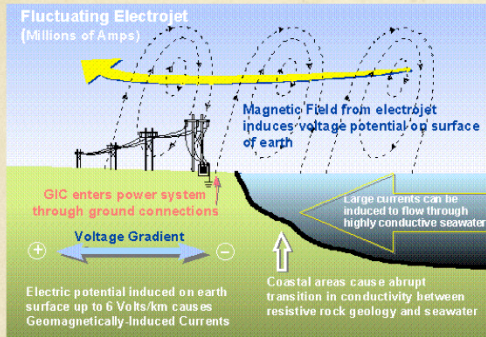
### Surface charging and resulting ESD

- spacecraft or surface potential elevated
- 2000-0800 local time in the plasma sheet
- regions of intense field-aligned currents
- observed, but not explained, at very low L



Janet Green, 2013

## Geomagnetically-Induced Currents



- power grids,
- oil and gas pipelines (increased corrosion)
- train light signals can be affected (two documented events in Sweden)



Damage to a transformer at a power plant in Delaware, New Jersey in March 1989 (10 MS)

## Synopsis I

The dynamics of Space Storms – defined by the interplanetary driver and the evolution of the Ring Current – and changes in the Van Allen Radiation Belts are intimately intertwined

Net Loss or Net Gain of relativistic  $e^-$  in the RBs is the synergistic result of collaborating / competing acceleration / transport / loss processes involving waves-particle interactions

## Synopsis II

Ultimately, relativistic electron enhancements result from source mechanisms dominating over loss mechanisms.

Frequent and intense substorms, although not capable of accelerating electrons to relativistic energies, play a crucial role through the supply of seed electrons and their role in chorus wave growth.

Frequent and intense substorms, characteristic of intense storms,

## Synopsis III

Taking into account that some waves account both for enhancements and for losses

(**Pc5** diffuse electrons both radially inwards and outwards)

**chorus** account for both  $e^-$  acceleration and  $e^-$  pitch angle scattering into the atmosphere loss cone)

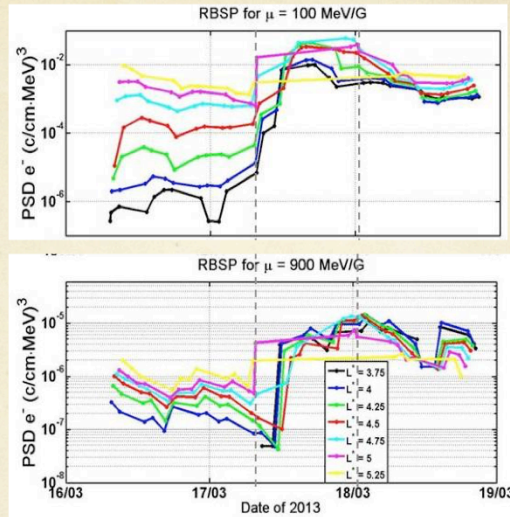
it becomes evident that comprehensive understanding and forecasting demands inquisitive research through data analysis, modeling and simulations

depending on PSD gradients

**Role of plasmasphere! (not touched in this presentation)**



## Storms and RB acceleration



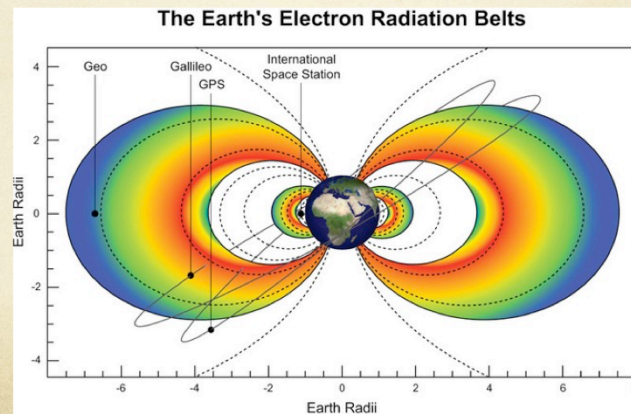
Pc5 and Chorus synergy  
resulting in net enhancement of relativistic electrons

## Van Allen Radiation Belts

Distinguished by their very high energies:

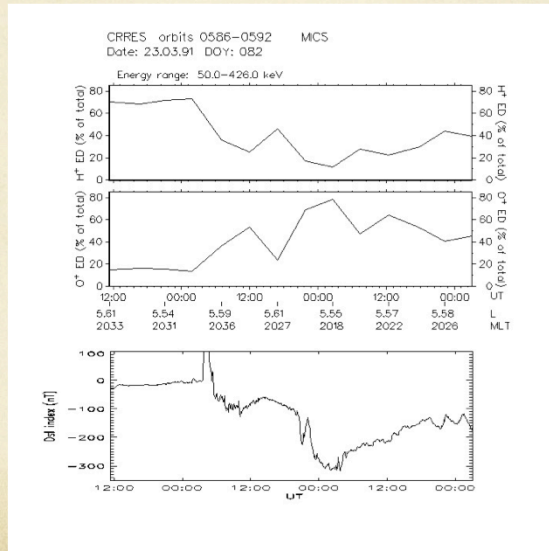
100 keV – 20+ MeV (400+ MeV)

and posing considerable threat to space assets



However: RBs have much higher energies.

## Ring current and magnetic storms

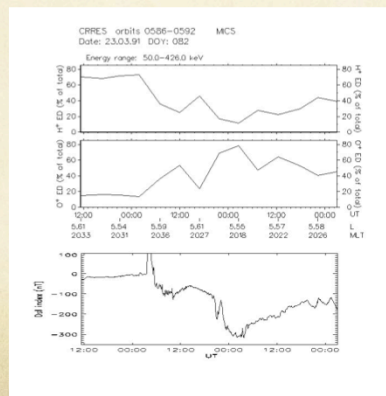


**An extreme example is the March 1991 storm, during which more than 70% of the RC energy density was provided by O<sup>+</sup> ions.**

## Ring current and magnetic storms

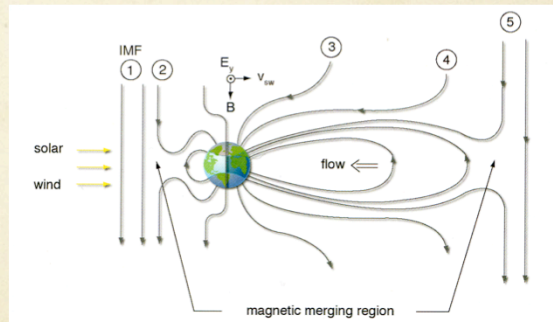
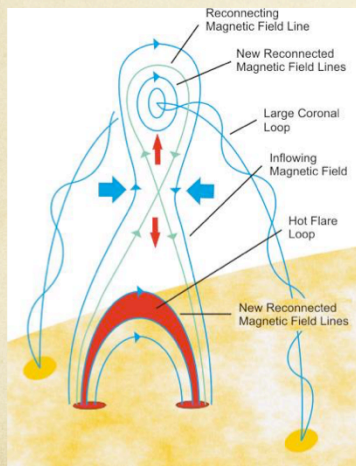
$O^+$  dominance leads to

- deeper Dst minima (greater storm magnitude)
- faster initial storm recovery



The  $O^+$  dominance (which is characteristic of intense storms) leads to ... **because  $O^+$  ions are lost faster than  $H^+$  (due to MP shadowing and charge-exchange)**

## Magnetic reconnection: Transforming magnetic to kinetic energy



**The fundamental process: Magnetic Reconnection on the Sun and in Geospace.**